The impact of nonlinear scattering effects on Doppler reflectometry and radial correlation Doppler reflectometry.

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Introduction

Turbulent transport plays a major role in plasma confinement, which makes understanding and control of plasma turbulence one of the major goals of fusion research. The tools for turbulence characterization include Doppler reflectometry (DR) and radial correlation Doppler reflectometry (RCDR) [1], latter of which utilizes simultaneous probing with two microwaves at different frequencies incident obliquely onto magnetic surface in the presence of the cutoff. As it was shown in [2, 3], at a large enough incidence angle by performing correlation analysis of backscattering signals, the information about turbulence properties can be extracted.

However, for both RCDR and conventional DR, analytical theory only predicts direct relation of measured quantities to turbulence characteristics in the linear regime of scattering [3], corresponding to low turbulence amplitudes. Some analytical results for nonlinear regime, such as criteria for the onset on nonlinearity [4, 5] and for transition to fully nonlinear regime corresponding to a saturation of the scattering signal power growth with the turbulence level were obtained for radial correlation reflectometry [6, 7] and for DR [8]. Nevertheless, the interpretation of experimental DR measurements is challenging in the nonlinear regime and in transition to it. Moreover, even for the linear scattering regime substantial contribution of the small-angle scattering off long-scale fluctuations in the scattering signal leads to the overestimation of radial correlation length [3, 7, 9]. Methods were, however, suggested to reconstruct the turbulence radial wavenumber spectrum from RCDR data [10, 11].

Overall, the mentioned difficulties of the DR data interpretation make full-wave numerical modeling one of the main tools of analysis of RCDR and DR. Numerical studies of the RCDR and DR were performed [12] and recently synthetic diagnostics allowing to compare gyrokinetic modeling results directly to experimental measurements were developed [13], [14]. One of such diagnostics was developed for the FT-2 tokamak [13] and demonstrated a good agreement with experimental data. This work highlights the results of these computations focusing on the effects of nonlinearity on the DR and RCDR measurements.

The computation approach and results

The parameters of FT-2 discharge used for gyrokinetic modeling are B_0=1.7 T, I_p=19 kA, n_e^{max}=4.2·10^{19} m^{-3}, while major and minor radii of the device are 55 cm and 8 cm respectively. This discharge was modeled by ELMFIRE GK code [15] and the resulting density profile was used for synthetic RCDR diagnostic. All the detail can be found in [13]. Realistic density perturbations, obtained with ELMFIRE code were multiplied by a constant factor to perform the scan over turbulence amplitude and observe, in a computation, a signature of the mentioned nonlinear effects. Calculations were carried out both for X-mode, as described in [13], with probing in 70 GHz frequency range being performed horizontally from the high-field side at a vertical shift of up to 2 cm from the mid-plane. In the case of O-mode the probing at a central frequency 30 GHz along vertical chord situated at 5 cm shift from the center of poloidal cross-section was modeled.

In case of X-mode, presented on fig. 1-3 calculations were performed for the ELMFIRE density fluctuations produced using an input electron temperature profile overestimating T_e in the probing wave cutoff (220 eV instead of actual experimental value of 100 eV). The turbulence obtained in this case possesses a narrower and steeper poloidal wavenumber spectrum, but is nevertheless realistic.

An example of DR spectra for a number of different turbulence amplitudes is plotted in the fig. 1, while fig. 2 demonstrates the dependence of the total scattered power received by antenna. Fig. 2 is plotted against the dimensionless factor a applied on the amplitude of the turbulence used in relation to the one produced by ELMFIRE code. That means that a=1 corresponds to original ELMFIRE turbulence, while a=2 means that turbulence was artificially enhanced twofold for full-wave computation.

It can be seen that with the growth or turbulence amplitude the DR spectra shifts to higher frequencies. This shift being caused by nonlinear effect is confirmed by signal power growing at a rate different from quadratic for the higher a values in the fig. 2. At about a=0.5 the growth becomes faster than predicted by linear theory, corresponding to nonlinear regime, described in [4, 5], while for a value of 1 and higher nonlinear saturation described by [6, 7] can be observed. The explanation we propose for these spectra shifts includes nonlinear dispersion of the turbulence leading to lower phase velocity at higher fluctuation poloidal wavenumbers observed in the GK computations as shown by green curve in fig. 4. For this kind of dispersion the multiple scattering off the lower-k fluctuations will provide a larger frequency shift than a single scattering off the fluctuation possessing the high poloidal wavenumber corresponding to linear regime.

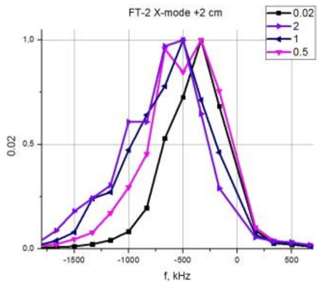

Fig. 1. DR power spectra for X-mode probing at antenna vertical shift +2cm.

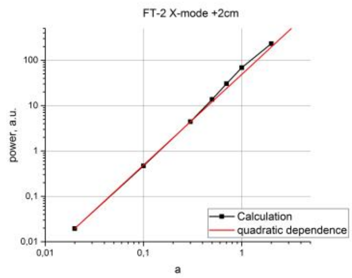

Fig. 2. DR power dependence on the turbulence amplitude.

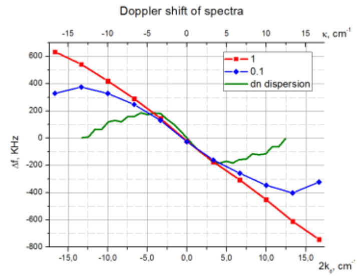

Fig. 3. Average frequency shift of scattering signal (red and blue) and direct ELMFIRE turbulence dispersion (green).

To confirm this idea, we considered the average DR signal spectrum frequency shift dependence on antenna position and consequently, poloidal wavenumber of the probing wave (as plotted at fig. 3). As argued above, in the linear regime we see a saturation of the Doppler frequency shift with growing probing poloidal wavenumber due to the turbulence dispersion law, while in the nonlinear regime we obtain linear dependence.

Therefore the effect nonlinear scattering has on DR frequency spectrum is “linearization” of the Doppler frequency shift dependence on poloidal wavenumber. The absence of “linearization” can be an indicator of the diagnostic operating in linear regime.

The effect of nonlinear scattering on DR poloidal wavenumber spectrum measurements and on RCDR is well described [6, 12, 14] and was reproduced in computations (performed in this case for experimental temperature profile). Broadening of power dependence on antenna vertical shift corresponding to poloidal wavenumber spectrum as well as narrowing of the CCF was observed in computation and can be seen on figs 4 and 5.

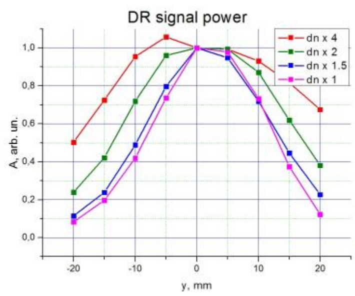

Fig. 4. DR power dependence on antenna vertical shift for different amplitudes of the turbulence.

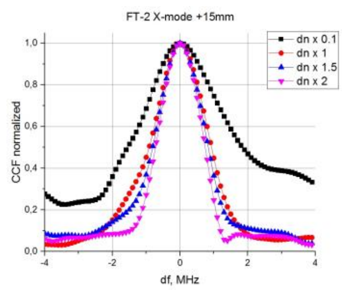

Fig. 5. Normalized RCDR CCFs for different amplitudes of the turbulence.

Another thing to note is that obtained results indicate that RCDR diagnostic transits into nonlinear regime at lower amplitudes of the turbulence compared to DR.

For O-mode computation, the fig. 6 demonstrates nonlinear narrowing of the RCDR CCF with the turbulence amplitude growth, suggesting linear regime of scattering for the original ELMFIRE data. As for the DR frequency spectrum, in the case of O-mode it still demonstrates the shift to higher frequencies in nonlinear regime, but nonlinear effects start to play a role at higher amplitudes compared to X-mode. The frequency spectra can be seen at fig. 7, while signal power dependence is presented at fig. 8.

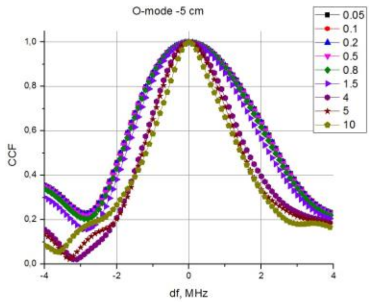

Fig. 6. O-mode RCDR CCF for -5 cm antenna shift for different amplitudes of the turbulence.

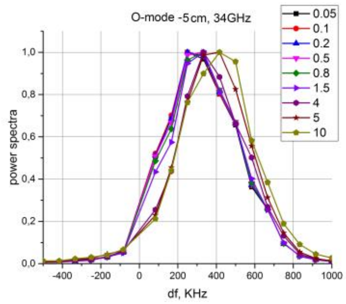

Fig. 7. DR power spectra for O-mode probing at 34 GHz for different amplitudes of the turbulence.

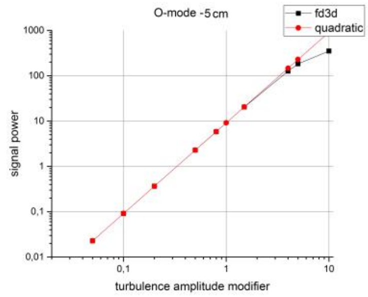

Fig. 8. DR signal power dependence on the turbulence amplitude.

Overall it seems that in the case of O-mode for the experimental situation both DR and RCDR operate within linear approximation, which makes linear numerical modeling relevant and means that O-mode measurements are suitable for direct interpretation.

Conclusions

Within this work the full-wave computations of synthetic DR and RCDR signals using a realistic FT-2 tokamak turbulence are performed. Nonlinear effects are demonstrated and found to be in agreement with theory. An effect of “linearization” of drift-wave dispersion by DR is found. Nonlinear effects are shown to be weaker for O-mode, while a faster transition to nonlinear regimes is demonstrated for RCDR compared to DR for both modes.

Acknowledgements

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